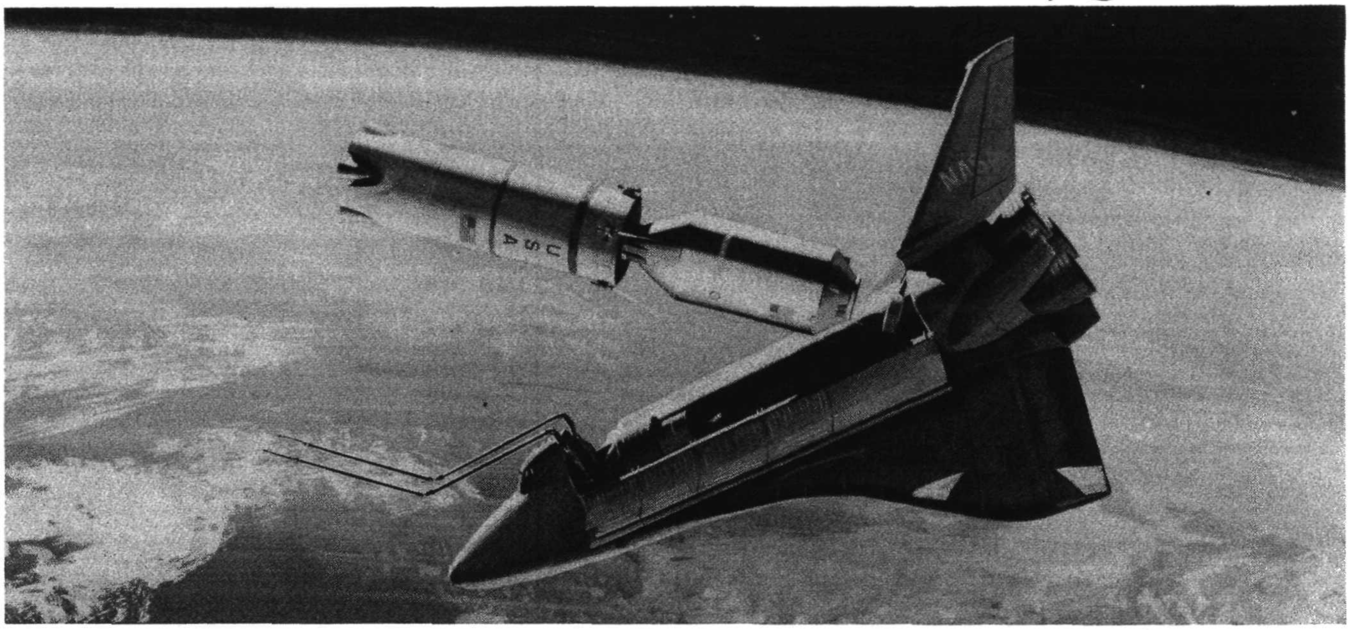
CONTRACT NAS8-27692
DR NO: MA-04

SD 72-SA-0053-1
JUNE 23, 1972

IN-SPACE PROPELLANT
LOGISTICS AND SAFETY

N72-30800



IN-SPACE PROPELLANT LOGISTICS

Volume I

EXECUTIVE SUMMARY

Space Division
North American Rockwell

12214 Lakewood Boulevard, Downey, California 90241

CONTRACT NAS8-27692
DR NO: MA-04

SD 72-SA-0053-1
JUNE 23, 1972

IN-SPACE PROPELLANT LOGISTICS AND SAFETY

IN-SPACE PROPELLANT LOGISTICS

Volume I

EXECUTIVE SUMMARY

R E Sexton

R.E. Sexton, PROGRAM MANAGER

Space Division
North American Rockwell

12214 Lakewood Boulevard, Downey, California 90241

FOREWORD

This In-Space Propellant Logistics and Safety Study was performed by the Space Division of North American Rockwell Corporation for the National Aeronautics and Space Administration, Marshall Space Flight Center, under Contract NAS8-27692. The study was a twelve-month effort initiated on 25 June 1971 and completed on 23 June 1972.

The study was conducted as two separate but related projects. One project addressed the systems and operational problems associated with the transport, transfer, and storage of cryogenic propellants in low earth orbits, while the other project addressed the safety problems connected with in-space propellant logistics operations. Correlation between the two projects was maintained by including safety considerations, resulting from the System Safety Analysis, in the trade studies and evaluations of alternate operating concepts in the Systems/Operations Analysis.

Walter E. Whitacre of Marshall Space Flight Center, Advanced Systems Analysis Office, was the Contracting Officer's Representative and provided technical direction to the overall contract and to the Systems/Operations Analysis project; Walter Stafford, of the same office, provided technical direction to the System Safety Analysis project. The contractor effort was under the direction of Robert E. Sexton, Program Manager; the Systems/Operations Analysis effort was led by Robert L. Moore and the System Safety Analysis effort was led by William E. Plaisted.

This document is Volume I of the following five volumes which contain the results of the Systems/Operations Analysis:

Volume I	Executive Summary	(SD72-SA-0053-1)
Volume II	Technical Report	(SD72-SA-0053-2)
Volume III	Trade Studies	(SD72-SA-0053-3)
Volume IV	Project Planning Data	(SD72-SA-0053-4)
Volume V	Cost Estimates	(SD72-SA-0053-5)

The results of the System Safety Analysis portion of the study are contained in the following three volumes:

Volume I	Executive Summary	(SD72-SA-0054-1)
Volume II	System Safety Guidelines and Requirements	(SD72-SA-0054-2)
Volume III	System Safety Analysis	(SD72-SA-0054-3)

CONTENTS

OVERVIEW

INTRODUCTION

The NASA space program plan (1975-1995) may encompass space-based and ground-based vehicles for transporting payloads from low-earth orbit to geosynchronous, lunar, and planetary orbit. The space-based vehicles require large quantities of propellants (primarily liquid oxygen and liquid hydrogen) and may be refueled periodically while in earth orbit. A representative space program plan was used to define the need for earth-to-earth orbit transport, earth orbital storage, and in-space transfer of these propellants. These functions were referred to as "in-space propellant logistics".

Vital steps in the successful development and execution of the space program plan used as the basis for this study is the early definition of the propellant logistics elements and the establishment of the date when initial operational availability would be required. In addition, funding requirements, schedules, and the impact on other program elements with respect to design and operational considerations must be defined for the timely and effective planning required to meet the overall goals and objectives of the space program.

To provide this vital information, an overall systems and operations analysis of the NASA space program plan with respect to in-space propellant logistics has been conducted and the results are reported herein.

The parametric nature of the basic data generated in this study is of potentially more value than the specific conclusions reached regarding the baseline propellant logistic system. These data should find many applications in the evaluation of future NASA space program plans.

OBJECTIVES OF THE STUDY

The overall objectives of the study were to perform a systems/operations analysis of activities and options in proposed NASA space programs from the standpoint of propellant logistics, and to develop and analyze concepts of orbital propellant logistics and determine the most cost effective approach. Specific objectives were to develop the following:

1. Time-phased in-space propellant quantity requirements of major elements
2. Cost effectiveness of orbital storage with and without an orbital storage depot
3. Impact of propellant payloads on the space shuttle payload requirements
4. Feasibility of promising in-space propellant transfer techniques

5. Credible in-space propellant logistics concepts and their cost effectiveness

6. The role of man associated with in-space propellant logistics

7. Equipment and interface requirements for the recommended concept and interfacing vehicles and a program implementation plan

8. Development of a program implentation plan.

STUDY APPROACH

The approach to the study is outlined in the flow diagram of Figure 1.

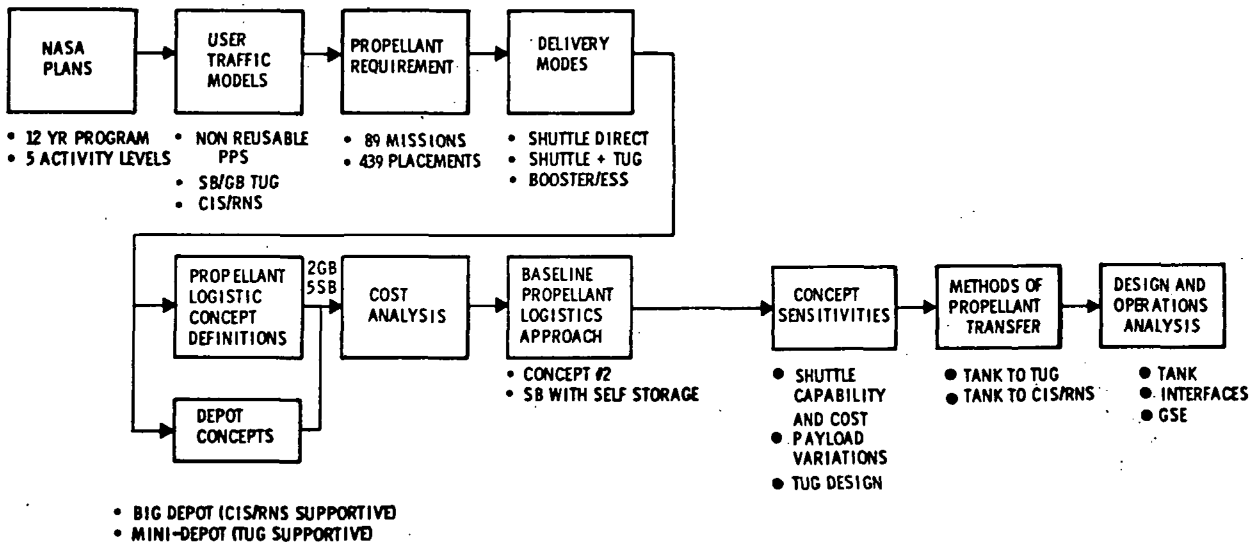


Figure 1. Study Approach

The study was based on an analysis of program plans for the accomplishment of NASA space missions in the period beginning with the availability of the Space Shuttle in 1979 and extending through 1990. The program plans were organized into five potential levels of activity designated A through E, in which Program Level A represents a relatively austere program and Program Level E the most vigorous one. These program activity levels represent a contraction and expansion of a set of NASA missions designated the "Fleming Model," dated 15 March 1972, which is included as Program Level C. Program Levels A through C include only earth orbital payload placement missions and planetary injection missions which do not require a CIS/RNS*. Program Levels D and E include automated and manned lunar missions as well as augmented planetary injection missions.

Vehicles considered for these missions include the space-based tug, the ground-based reusable tug, and nonreusable ground-based stages including the solid propellant FW-4S, the Agena, and the Centaur. The CIS or RNS vehicles

* Chemical Interorbital Shuttle/Reusable Nuclear Stage

are used in the manned lunar and augmented planetary injection missions. Assuming various vehicle availability dates and utilization models, traffic rates and propellant requirements were developed for each program mission level.

Subsequently, candidate operational concepts were developed for handling and storing propellants in space. A propellant module concept to carry propellant in the shuttle cargo bay was also developed. Candidate propellant transfer concepts were evaluated and the feasibility of orbital propellant transfer was established. Large depots were evaluated for use in support of the CIS and the RNS in their lunar missions, and small depots were evaluated for use with the space-based tug alone.

Seven propellant logistic concepts were defined for accomplishment of the earth orbital payload placement missions in the program. Logistic program costs were developed for each of these concepts and used to evaluate the various modes, with and without orbital storage.

The evaluation of the seven propellant logistic concepts led to the selection of Concept 2, which employs the space-based tug in a self storage mode, as the preferred concept for further development and study. The sensitivity of this concept was examined with regard to variations in shuttle payload capability and cost, increases in scientific payload length and weight, and variation in tug design. Subsequently, the design concept for the logistic module and its interfaces with the shuttle and with the user vehicles was developed in greater detail. An implementation plan was prepared which defines the program steps, including supporting research and technology and associated costs.

CONCLUSIONS

The significant conclusions that resulted from the study are summarized as follows:

1. Approximately 70% of the proposed shuttle payload traffic is propellant.

2. Some form of in-space propellant storage is required for the most cost-effective space program. A self-storage concept for a space-based tug operation and for CIS/RNS operation satisfies the requirement for in-space propellant storage. Therefore, an orbiting propellant depot is not required.

3. Propellant delivery with the shuttle orbiter, utilizing a propellant logistics module in the cargo bay, is more cost effective than delivery with the booster/ESS (expendable second stage) combination even for large user vehicles such as CIS and RNS.

4. In-space propellant transfer is feasible within the present state of the art. The technology should be improved for high performance, low thrust propulsion systems required for propellant settling, and for low gravity propellant quantity sensing.

5. The propellant logistics requirements are expected to have only nominal impact on interfacing vehicles, such as shuttle, tug, and CIS or RNS, to provide for fill, vent, drain, pressurization, emergency dump, command and control connections, and insulation purge.

6. The role of man required for in-space propellant transfer is within the normal operational duties associated with space shuttle operations.

7. The Phase D effort required for providing a propellant logistics module should start in early 1979 for an in-space propellant logistics capability by 1985.

8. Propellant logistics costs are driven by shuttle operational costs.

DISCUSSION OF DATA

IN-SPACE PROPELLANT REQUIREMENTS

The first task accomplished in the evaluation of in-space propellant logistics was the definition of five NASA space program mission levels. The composition of each program level developed is summarized in Figure 2. This range of activity provides a parametric base for the establishment of flight rate influence on propellant logistics requirements.

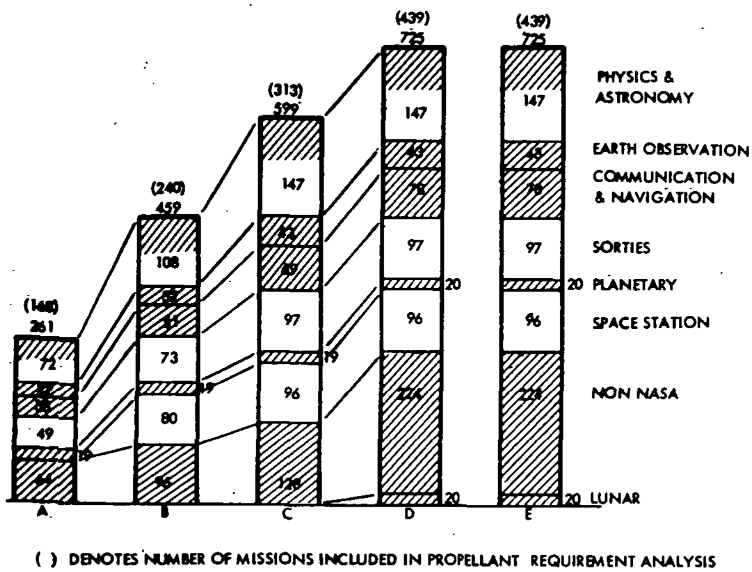


Figure 2. Program Mission Level Composition Guide

Each column in Figure 2 has been divided to indicate the relative number of payload placements in each mission category (physics and astronomy, earth observation, etc.) for the five program activity levels. The shaded portion of each column represents the payload placements which impose in-space propellant requirements; these are summarized by the numbers in parenthesis at the top of each column. The unshaded portions represent all space station, all sortie, and part of the physics and astronomy missions which do not contribute to in-space propellant requirements. These missions can be performed by the shuttle alone. The larger number at the top of each column is the sum of all the placements and retrievals in each program level over the 12-year period from 1979 to 1990.

The NASA space program models include earth orbital payload placement missions to be performed by a tug or other payload propulsive stage and lunar missions to be performed by the CIS or RNS. The earth orbital mission model was based on the use of the space shuttle orbiter to carry a scientific payload to 100 n.mi. circular orbit with some type of payload propulsive stage (PPS) delivering the payload to the final desired orbit from that point. Two general concepts of scientific payload placement were considered: (1) use of nonrecoverable or expendable stages such as the solid propellant FW-4S, the Agena, or the Centaur, and (2) use of recoverable stages, such as the ground-based or the space-based tug. The option of payload propulsive stages and varying availability dates resulted in 13 program implementation plans, as shown in Table 1, that were analyzed for in-space propellant requirements. The characteristics of the payload propulsive stages are illustrated in Figure 3.

Space traffic models were prepared for each program implementation plan. Each traffic model lists the number of flights required for each mission, by year, for the 12-year period under analysis (1979-1990) and indicates the payload propulsive stage to be used. Table 2 presents a representative portion of the traffic model for Program Level C (the Fleming model). Similar traffic models were prepared for all five program mission levels and are presented in Volume II. The space traffic models, once established, were the basis for all subsequent calculations of propellant requirements, propellant logistics traffic models, cost analysis, and sensitivity studies.

Table 1. Program Implementation Plan

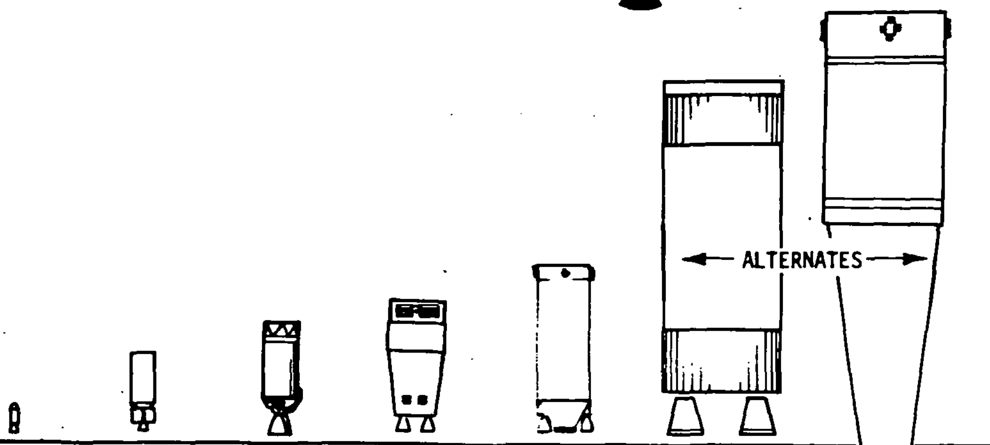
PROGRAM LEVEL (WITH DESIGNATOR)	PAYLOAD PROPULSIVE STAGE 1979-1984	PAYLOAD PROPULSIVE STAGE 1985-1990
A_1	EXPENDABLES	EXPENDABLES
B_1	EXPENDABLES	G. B. TUG
B_2	EXPENDABLES	S. B. TUG
C_1	EXPENDABLES	G. B. TUG
C_2	EXPENDABLES	S. B. TUG
D_1	EXPENDABLES	G. B. TUG
D_2	EXPENDABLES	S. B. TUG
D_3	G. B. TUG	G. B. TUG
D_4	S. B. TUG	S. B. TUG
E_1	EXPENDABLES	G. B. TUG
E_2	EXPENDABLES	S. B. TUG
E_3	G. B. TUG	G. B. TUG
E_4	S. B. TUG	S. B. TUG

The delta V required to place each payload in its operational orbit (from 100 n.mi. earth orbit) and the performance characteristics of the designated payload propulsive stage for the placement were used to compute the propellants required for each placement. Although the space traffic models included missions that could be carried out by the shuttle orbiter alone, such missions were not included in the calculation of propellant quantities, since they did not require in-space propellant logistics. The initial propellant requirements were established by nearly 200 individual placement calculations and were summarized, by mission and by year, for each implementation plan. The resultant time-phased propellant requirements provide the basis for the subsequent propellant logistics operations analysis. Time-phased propellant requirements thus calculated for the 1979-1990 time period are presented in Figure 4, This figure is for the case of nonreusable payload propulsive stages in the 1979-1984 time period and space-based tug for the 1985-1990 time period; it also includes the propellant requirements for the CIS/RNS options during the 1985-1990 time period. Rates as high as 5 million pounds per year are required. Similar data for the other implementation options are to be found in Volume II.

The total quantities of propellants required to be delivered in space for the various program implementations are impressive, not only in terms of total weight but also in terms of their relationship to the total cargo delivered to space. Cryogenic propellants for either a ground-based or a space-based tug represent the major cargo for the space shuttle. For Program Level D, for example, propellant is from 68% to 77% of the total cargo carried. Figure 5 summarizes shuttle propellant payload requirements for Program Level D.

PROPELLANT DELIVERY MODES

One of the fundamental questions examined for this study was the cost of delivery of propellant to space by various candidate methods. The objective of the delivery technique was to provide propellant to a user



CHARACTERISTICS	FW4S	AGENA	CENTAUR	TUG (OOS)	SPACE TUG	CIS	RNS
	GROUND-BASED				SPACE-BASED		
LENGTH - FT	6.8	20	31.5	36	47	100	194
DIAMETER - FT	2.1	5	10	15	15	33	33
WEIGHTS - LB							
GROSS	860	15000	35,300	67,500	83,4[illegible]0	1,095,000	377,000
PROPELLANT	—	13600	30,200	60,200	73,2[illegible]0	990,000*	300,000*
EXPENDABLE	X	X	X				
REUSABLE				X	X	X	X
IN SPACE PROP. RECEIVER					X	X	X

*LUNAR MISSION MODE 1 REQUIREMENTS

Figure 3. Payload Propulsive Stages

Table 2. Program Level C Space Traffic Model Data (Part 1)

MISSION CATEGORY	NO.	MISSION TITLE	ORBIT INCL (°)	ORBIT ALT (nmi)	PAYLOAD DIA X L (FT)	MISSION PAYLOAD LB	ΔV ABOVE 100 X 100 FT/SEC ①	PROPULSIVE STAGE(S) ABOVE SHUTTLE 79-84	PROPULSIVE STAGE(S) ABOVE SHUTTLE 85-90	79	80	81	82	83	84	85	86	87	88	89	90	12-YEAR TOTAL
PHYSICS & ASTRONOMY	1.	ASTRONOMY EXPLORER	28.5	270	1.7 x 2.5	720	592	NONE	NONE	2		1	2	2	1		2	1	2	2		15
	2.	RADIO EXPLORER	28.5	19300	4.5 x 3.3	720	13,000	AGENA	TUG		2	1			1	2		1			2	9
	3A.	MAGNETOSPHERE EXPLORER	0	1800 x 180	4 x 8	1,200	11,783	AGENA	TUG	1				1				1				3
	3B.	MAGNETOSPHERE EXPLORER	28.5	1800 x 180	4 x 8	1,200	2,510	FW-4S	TUG		1				1				1			3
	3C.	MAGNETOSPHERE EXPLORER	55	1800 x 180	4 x 8	1,200	2,510	FW-4S	TUG			1				1				1		3
	3D.	MAGNETOSPHERE EXPLORER	90	1800 x 180	4 x 8	1,200	2,510	FW-4S	TUG				1				1				1	3
	4A.	MAGNETOSPHERE EXPLORER	0	20000 x 1000	5 x 8	1,000	11,158	AGENA	TUG	1				1				1				3
	4B.	MAGNETOSPHERE EXPLORER	28.5	20000 x 1000	5 x 8	1,000	10,720	AGENA	TUG		1				1				1			3
	4C.	MAGNETOSPHERE EXPLORER	55	20000 x 1000	5 x 8	1,000	10,720	AGENA	TUG			1				1				1		3
	4D.	MAGNETOSPHERE EXPLORER	90	20000 x 1000	5 x 8	1,000	10,720	AGENA	TUG				1				1				1	3
	5A.	MAGNETOSPHERE EXPLORER	0	1 AU	4 x 6	600	13,099	AGENA	TUG	1				1				1				3
	5B.	MAGNETOSPHERE EXPLORER	28.5	1 AU	4 x 6	600	11,000	AGENA	TUG		1				1				1			3
	5C.	MAGNETOSPHERE EXPLORER	55	1 AU	4 x 6	500	11,000	AGENA	TUG			1				1				1		3
	5D.	MAGNETOSPHERE EXPLORER	90	1 AU	4 x 6	600	11,000	AGENA	TUG				1				1				1	3
	6.	ORBITING SOLAR OBSERVATORY	30	350	7 x 10	1,900	856	NONE	NONE		1											1
	7A.	GRAVITY/RELATIVITY EXP	85	300	5 x 7	1,500	692	NONE	NONE						1							1
	7B.	GRAVITY/RELATIVITY EXP	95	300	5 x 7	1,500	692	NONE	NONE												1	1
	8.	GRAVITY/RELATIVITY EXP	28.5	1 AU	4 x 5	500	11,000	AGENA	TUG			1						1				2
	9.	RADIO INTERFEROMETER	28.5	38646	12 x 15	6,000	13,660	CENTAUR	—			1										1
	10.	SOLAR ORBIT PAIR	30	19300	10 x 12	1,900	12,917	AGENA	TUG						1					1		2
	11.	SOLAR ORBIT PAIR	28.5	1 AU	10 x 12	1,900	11,000	AGENA	TUG						1					1		2
	12.	OPTICAL INTERFEROMETER	30	19300	7 x 10	3,500	12,917	—	TUG										2			2
	13A.	HEAO	30	230	10 x 34	19,730	468	NONE	NONE	1				1		1						3
	13B.	HIGH ENERGY STELLAR ASTR.	30	230	14 x 46	21,000	468	NONE	NONE				1					1		1		3
	14.	HESA REVISITS	30	230	14 x 13	3,500	468	NONE	NONE		2	2	2	2	2	2	2	2	2	2	2	22
	15A.	LST (STAR)	28.5	350	13 x 45	21,300	856	NONE	NONE			1				1						2
	15B.	LST (RAM)	28.5	350	14 x 60	30,000	856	NONE	NONE							1						1
	16.	LST (REVISITS)	28.5	350	14 x 13	3,500	856	NONE	NONE				2	2	2	1	2	2	2	2	2	17
	17.	LARGE SOLAR OBSERVATORY	30	350	14 x 54	27,300	856	NONE	NONE					1					2			3
	18.	(LSO REVISITS)	30	350	14 x 13	3,500	856	NONE	NONE						2	2	2	2	1	2	2	13
	19.	LARGE RADIO OBSERVATORY	30	350	14 x 30	19,300	856	NONE	NONE							1						1
	20.	(LRO REVISITS)	30	350	14 x 13	3,500	856	NONE	NONE								2	2	2	2	2	10
EARTH OBSERVATION	21.	POLAR EARTH OBS. SAT.	99.15	500	6 x 12	2,500	1,330	FW-4S	TUG	1	1	1	1	1	1	1	1	1	1	1	1	12
	22.	SYNCH. EARTH OBS. SAT.	0	19300	4 x 6	1,000	14,100	AGENA	TUG		1		1		1		1		1		1	6
	23.	EARTH PHYSICS SAT.	90	400	3.5 x 6.5	600	1,020	FW-4S	TUG		1	1	1	1		1		1		1		7
	24.	SYNCH. METEOROLOGICAL SAT.	0	19300	5 x 8	1,000	14,100	AGENA	—				1	1								2
	25.	TIROS	100.7	700	5 x 10	1,000	1,940	FW-4S	TUG			1				1					1	3
	26.	POLAR EARTH RESOURCES SAT.	99.15	500	6 x 12	2,500	1,330	—	TUG								2	4				6
	27.	SYNCH. EARTH RESOURCES SAT.	0	19300	4 x 6	1,000	14,100	AGENA	TUG			1	2	1				1	2			7
COMMUNICATION/NAVIGATION	28.	APPLICATIONS TECH. SAT.	0	19300	15 x 20	7,950	14,100	CENTAUR	2 TUGS ②	1		1		1	1		1		1	1		7
	29.	SMALL APPLICATIONS SAT.	0	19300	6.5 x 12	600	14,100	AGENA	TUG	1	1	1	1	1	1	1	1	1	1	1	1	12
	30.	SMALL APPLICATIONS SAT.	90	3000 x 300	6.5 x 12	600	3,800	FW-4S	TUG	1	1	1	1	1	1	1	1	1	1	1	1	12
	31.	COOPERATIVE APPLICATIONS	0	19300	6.5 x 12	820	14,100	AGENA	—	1					1							2
	32.	COOPERATIVE APPLICATIONS	90	3000 x 300	6.5 x 12	820	3,800	FW-4S	TUG				1							1		2
	33.	MEDICAL NETWORK SAT.	0	19300	12 x 15	2,000	14,100	AGENA	—	2												2
	34.	EDUCATION BROADCAST SAT.	0	19300	10 x 19	2,145	14,100	AGENA	—		2											2
	35.	FOLLOW-ON SYSTEM DEMO.	0	19300	12 x 15	2,000	14,100	AGENA	TUG			2	2	2	2	2	2	2	2	2	2	20
	36.	TRACKING & DATA RELAY	0	19300	12 x 15	2,300	14,100	AGENA	TUG	1	2	1		2	1			2	1			10
	37.	PLANETARY RELAY SAT.	0	19300	10 x 20	1,000	14,100	—														0

① THEORETICAL MINIMUM, ONE-WAY, POINT-TO-POINT ΔV
② ASSEMBLED IN SPACE

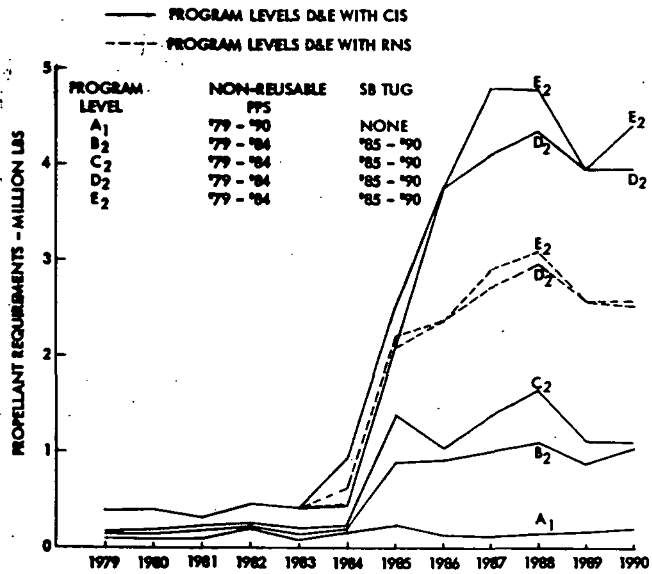


Figure 4. PPS Propellant Requirements for Space-Based Tug Available in 1985

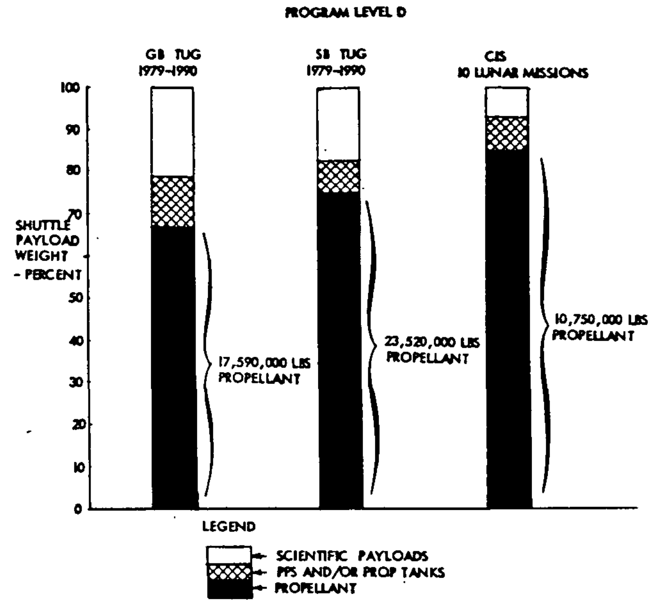
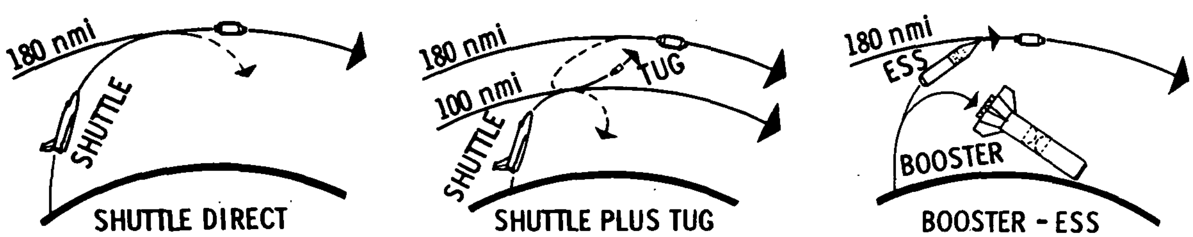


Figure 5. Shuttle Propellant Payload Requirements for Level D

vehicle, either a space-based tug or CIS/RNS, in a parking orbit at 180 n.mi. altitude. Three candidate delivery modes were examined: (1) shuttle delivery of a propellant logistics module direct to 180 n.mi. altitude; (2) shuttle delivery of a propellant module to 100 n.mi. altitude with a space-based tug used to carry the module to 180 n.mi. altitude, and (3) an expendable second stage (ESS) used in conjunction with the shuttle booster to carry a larger quantity of propellant to 180 n.mi. The delivery of oxygen and hydrogen for refueling a tug or CIS and the delivery of hydrogen only for support of an RNS were considered. The results of an analysis are shown in Figure 6. The calculation of the propellant delivered by the various modes includes allowances for container weight, propellant in the tank, propellant required for tug operation (if needed), and transfer losses to the receiver vehicle. The delivery costs include shuttle launch costs, tank costs amortized per mission, and tug operation costs. However, ESS development costs are not included. The net result is the dollars per pound cost of propellant delivered to the user at 180 n.mi.

The data indicate that direct delivery of propellants by the shuttle alone to an altitude of 180 n.mi. is the most economical delivery mode at $178 per lb for the combination of oxygen and hydrogen propellant required to support the tug or CIS vehicles. This mode is cheaper than delivery by the tug in conjunction with the shuttle or by the shuttle booster with an expendable second stage. The latest performance data on the proposed



DELIVERY MODE	OXYGEN & HYDROGEN TUG/CIS SUPPORTIVE		HYDROGEN RNS SUPPORTIVE	
	PROPELLANT DELIVERED	$/LB	PROPELLANT DELIVERED	$/LB
SHUTTLE DIRECT	56.9 K LB	$178	32.3	314 ($235 WITH EXTERNAL TANKS)
SHUTTLE & TUG	54.4	210	31.6	363
BOOSTER-ESS	175.0	245	175.8	237

Figure 6. Propellant Delivery Methods

shuttle, as of March 1972, indicate that it can carry 65,000 lb of payload to higher than 180 n.mi. by the use of its on-board hypergolic OMS propellant. The altitude of 180 n.mi. is used because it is the selected parking orbit altitude for the space-based tug, the candidate depots, and for the CIS and RNS.

In the case of the shuttle booster and expendable second stage, the much larger payload that can be carried by the second stage is not sufficient to offset the cost of its expenditure.

For the delivery of hydrogen, the shuttle cargo bay is limited in volume and the logistics module can carry only about 30,000 lb. This limitation accounts for the higher shuttle delivery costs for the hydrogen case. Delivery of hydrogen by the booster/ESS, which does not have the same volume limitation, is cheaper than delivery of hydrogen in the shuttle cargo bay. However, the use of additional external hydrogen tanks on the shuttle could reduce the costs for hydrogen delivery to about $235 per lb, which would be competitive with the use of the booster/ESS. Direct delivery of propellant by the shuttle was used as the baseline delivery mode throughout the remainder of the study.

CIS/RNS LUNAR MISSIONS

A major question examined was the need for an in-space propellant depot to support the CIS/RNS vehicles for lunar missions. Since the acquisition, deployment, and maintenance of an orbital storage facility (depot) represent

an added cost as far as orbital operations are concerned, a depot is cost-effective only if its presence reduces the cost of the other operations. Because the CIS configuration used in the study holds about one million pounds of propellant, a CIS supportive depot would be very large. If a CIS depot were required, it could also support the tug for its scientific payload placement missions and thus would influence the analysis of tug operations. However, the analyses conducted and summarized in the following paragraphs demonstrate that a separate orbital storage depot to support either the CIS or the RNS is not cost-effective.

The number of shuttle vehicles dedicated to CIS propellant resupply is determined by the time available for refueling and the number of trips each shuttle can perform during this period. Therefore, a tradeoff exists between the number of dedicated shuttles and a separate orbital propellant storage facility. For the purpose of this study, a CIS lunar flight rate of two per year was used as a baseline requirement. Based on a 15-day flight interval for each shuttle supporting CIS refueling and an 80% operational availability, two dedicated shuttles are required. If the CIS flight rate increased to four flights per year, seven dedicated shuttles would be required because of the reduced time available for refueling. (Note that approximately 18 shuttle flights are required to refuel the CIS for each lunar mission.)

Some form of in-space propellant storage for CIS could reduce the number of shuttles required to support a high CIS flight rate by increasing the time available for refueling. This storage requirement could be met more economically, however, by operating with two space-based CIS's rather than with a depot.

Figure 7 shows the savings in shuttle acquisition costs as a function of CIS lunar flight rate assuming separate orbital storage is available. Superimposed on the plot are the costs of two different storage techniques: a special orbital propellant depot, and use of a second CIS instead of a depot. The data show that a second CIS becomes cost-effective at a rate of approximately two CIS flights per year (45-day mission duration). A separate depot becomes cost-effective at approximately three flights per year (based on depot costs previously developed by NR). However, even at a rate of three or more CIS flights per year, a second CIS would be more cost-effective than a separate depot.

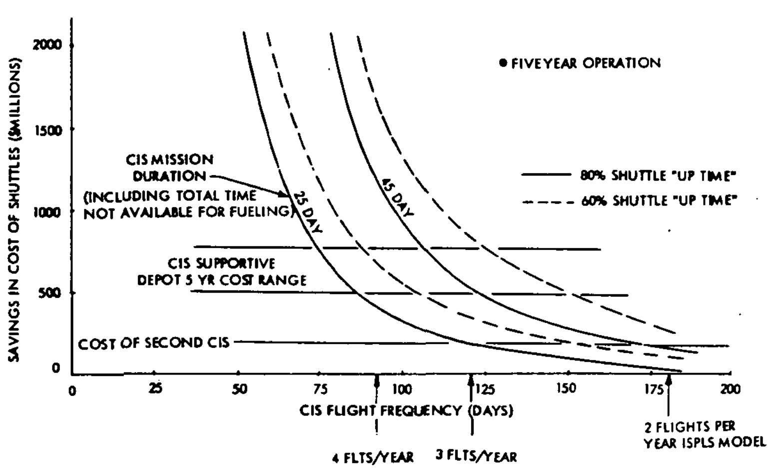


Figure 7. Savings in Shuttle Acquisition Costs by CIS Operation with Depot or Second CIS

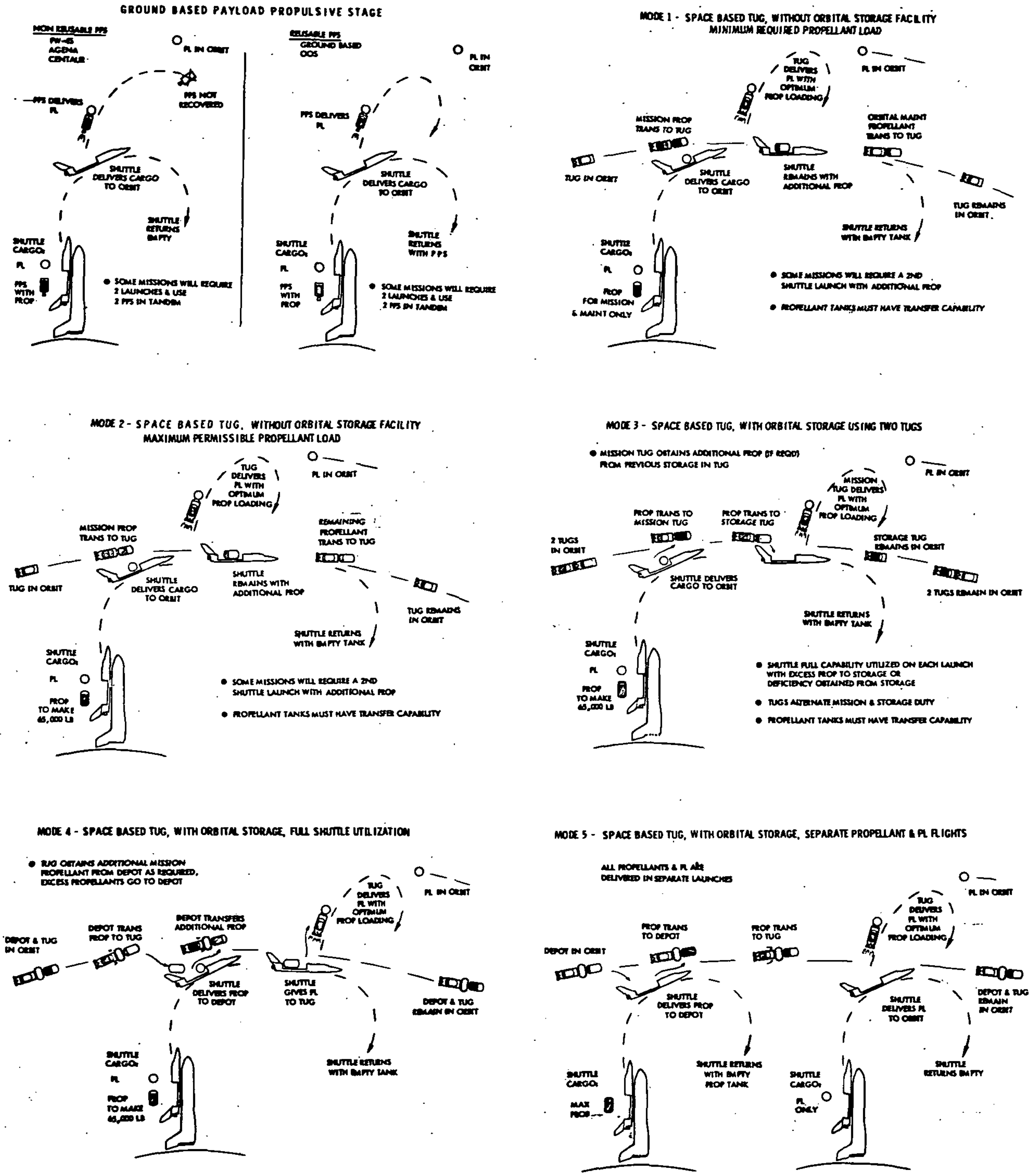


Figure 8. Propellant Logistics Concepts

TUG/PPS SCIENTIFIC PAYLOAD PLACEMENT MISSIONS

Seven candidate propellant logistics concepts were defined for supporting scientific payload placement missions. (Refer to Figure 3 for placement vehicle identification.) These concepts are illustrated in Figure 8 and their operational descriptions are contained in Table 3. The latter includes a summary of the number of scientific payload placements in each program activity level during the 1985-1990 time period and the number of supporting shuttle flights required for these placements with each propellant logistics concept.

Cost comparisons for propellant logistic support of the space traffic model for Program Level C, using the seven candidate operational concepts, are summarized separately for easterly launches in Figure 9 and for polar launches in Figure 10. The costs shown include production and operation costs for shuttle, tug, and other vehicles prorated on a unit cost per flight basis. The cost of the propellant used is included in terms of the cost of the number of shuttle flights required to transport the propellant to earth orbit; and the costs of development, production, and operation for dedicated propellant logistics hardware (e.g., logistic tank modules) are also taken into consideration. The costs of the scientific payloads and experiments are not included.

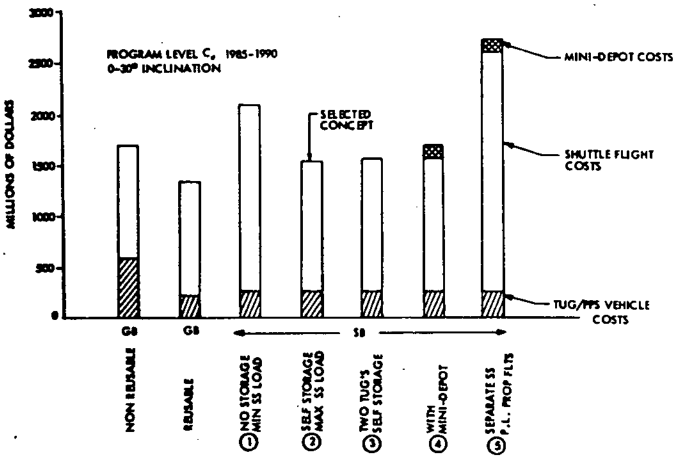


Figure 9. Logistic Program Costs for Easterly Launches

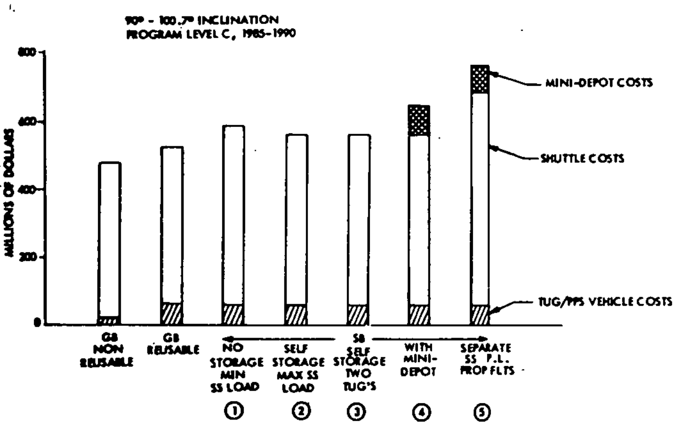


Figure 10. Logistic Program Costs for Polar Launches

Concept 2 is the most cost-effective of the five space-based concepts and was therefore selected for further development and analysis. Concept 2 is depicted schematically in Figure 8 and may be seen with more clarity in Figure 11. One potential disadvantage of the selected concept is the requirement for the shuttle to remain in orbit until the tug has completed its payload placement mission. If this turns out to be an unacceptable operational complexity, Concept 3 could be used instead with essentially no increase in program costs.

Table 3. Propellant Logistic Operational Concepts and Number of Supporting Shuttle Flights for PPS Placement of Scientific Payloads, 1985-1990

	LOGISTICS OPERATION CONCEPT DESIGNATION	OPERATIONAL DESCRIPTION	NO. OF SHUTTLE SUPPORTING FLIGHTS FOR PROGRAM LEVEL: A	B	C	D	E
SPACED BASED REUSABLE PAYLOAD PROPULSIVE STAGES	1 ONE TUG, NO STORAGE	SHUTTLE CARRIES PROPELLANT FOR ONE PLACEMENT ONLY BY TUG PLUS BETWEEN MISSION TUG STATION KEEPING. SOME PLACEMENTS REQUIRE SECOND SHUTTLE FLIGHT BUT FOR MOST PLACEMENTS THE FULL SHUTTLE CAPABILITY IS NOT USED THUS AN IN-EFFICIENT, COMPARATIVELY COSTLY CONCEPT	*	180	243	350	339
	2 ONE TUG, SELF STORAGE	SAME AS CONCEPT 1 EXCEPT SHUTTLE CARRIES THE MAXIMUM 65K LBS PAYLOAD ON EVERY SUPPORTIVE FLIGHT PROPELLANTS IN EXCESS OF THOSE FOR THE NEXT PLACEMENT ARE TRANSFERED TO AND STORED IN THE TUG UPON RETURN FROM THE PLACEMENT. SHUTTLE STANDS BY DURING TUG MISSION. VERY EFFICIENT USE OF SHUTTLE, REDUCES SHUTTLE SUPPORT FLIGHTS FROM CONCEPT 1 THUS INDICATING AN ADVANTAGE TO ORBITAL STORAGE	*	139	184	247	238
	3 TWO TUGS	SAME AS CONCEPT 2 EXCEPT THAT A SECOND TUG IS SPACE BASED AND EXCESS PROPELLANTS ARE TRANSFERRED TO IT FOR STORAGE AND THE TUGS ALTERNATE FOR PLACEMENT MISSIONS. REQUIRES MORE PROPELLANTS THAN CONCEPT 2 FOR DOUBLE STATION KEEPING. PROVIDES SOME OPERATIONAL FLEXIBILITY	*	140	186	249	239
	4 ONE TUG PLUS MINI DEPOT	SAME AS CONCEPT 3 EXCEPT THAT ORBITAL STORAGE OF EXCESS PROPELLANTS IS PRO-VIDED BY A MINI-DEPOT CONSISTING OF AN EQUIPMENT MODULE (WHICH PROVIDES STATIONKEEPING, RENDEZVOUS, DOCK, PROPELLANT SETTLING AND TRANSFER CAPABILITY) AND A SHUTTLE CARGO BAY PROPELLANT LOGISTIC TANK. SAME PROPELLANT REQUIREMENTS AS CONCEPT 3 ADDED COST OF MINI-DEPOT	*	140	186	249	239
	5 ONE TUG PLUS MINI-DEPOT SEPARATE SHUTTLE FLIGHTS FOR 1) SCIENTIFIC PL 2) PLACEMENT PROPELLANTS FOR SCIENTIFIC PL PLACEMENT	SAME AS CONCEPT 4 EXCEPT FOR THE GROUND RULE THAT SCIENTIFIC PAYLOAD AND PROPELLANT PAYLOAD MUST BE TRANSPORTED TO EARTH ORBIT BY SEPARATE SHUTTLE FLIGHTS. GROUND RULE IS ADDRESSED TO MISSION PLANNING FLEXI-BILITY BUT RESULTS IN INEFFICIENT USE OF SHUTTLE PAYLOAD CAPABILITY MEDIAN SCIENTIFIC PL IS 12 FT LONG AND WEIGHS ONLY 1000 LBS). REQUIRES SIGNIFICANTLY MORE SHUTTLE FLIGHTS	*	233	307	426	410
GROUND BASED PAYLOAD PROPULSIVE STAGES	NON-REUSABLE PAYLOAD PROPULSIVE STAGES (FW-4S, AGENA OR CENTAUR)	THE PAYLOAD PROPULSIVE STAGES (PPS) IDENTIFIED, INCLUDING THEIR PROPELLANTS REQUIRED FOR THE PLACEMENT MISSION, AND THE SCIENTIFIC PAYLOAD FOR PLACE-MENT, ARE CARRIED TO LOW EARTH ORBIT IN THE SHUTTLE CARGO BAY. THE PPS IS EXPENDED IN PLACING THE SCIENTIFIC PAYLOAD IN HIGH ORBIT. THE LEAST EXPENSIVE PPS HAVING THE NECESSARY PERFORMANCE CAPABILITY IS USED FOR A GIVEN PLACEMENT. FOR SOME PLACEMENTS TWO CENTAURS IN TANDEM (WITH INTERFACE STRUCTURE) ARE REQUIRED, ALSO REQUIRING TWO SHUTTLE FLIGHTS	95	127	167	*	*
	REUSABLE PAYLOAD PROPULSIVE STAGE (G.B. TUG)	SAME AS FOR GB NON-REUSABLE PPS EXCEPT THAT AFTER PL PLACEMENT, THE SHUTTLE RETRIEVES THE TUG AND RETURNS IT TO EARTH	*	125	166	221	212
	NUMBER OF PAYLOAD PLACEMENTS IN PROGRAM LEVELS		85	117	157	211	206

* CASES NOT RUN

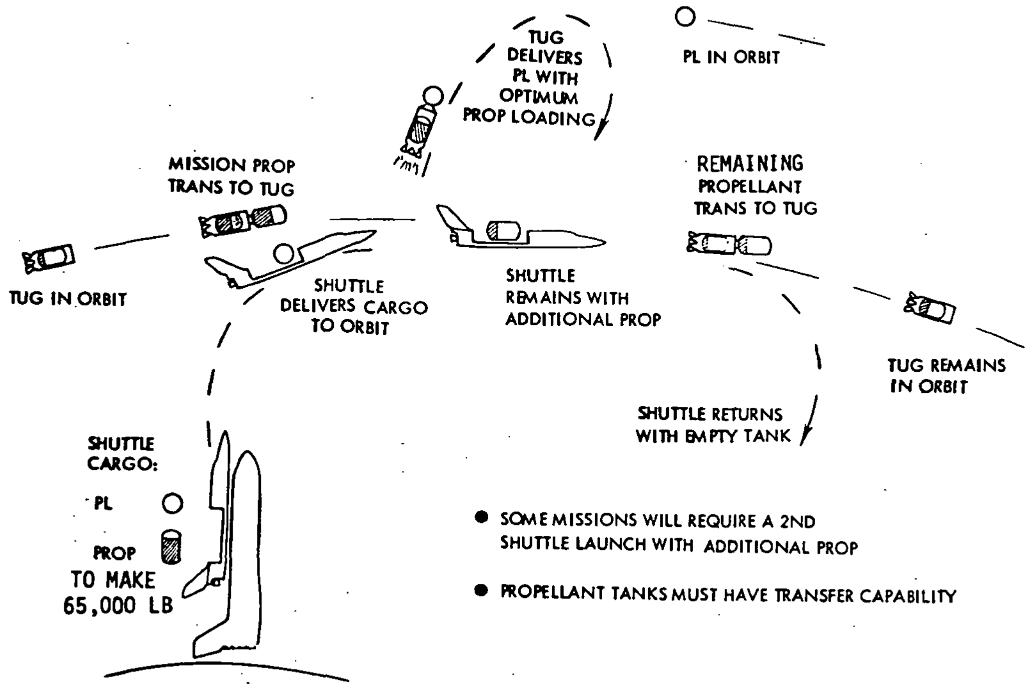


Figure 11. Operational Concept 2 for Payload Delivery with Space-Based Tug, Self Storage

The ground-based reusable payload propulsive stage is the most cost-effective of all the concepts for the conditions analyzed. Two factors must be considered with respect to these conclusions:

1. It is shown in the sensitivity studies in the next section that the use of a tug lighter in weight than the space-based tug baselined for this study will reduce the costs for Concept 2 to slightly less than those for the ground-based reusable mode.

2. The mission model does not include any payload retrieval missions. It is also shown in the sensitivity studies that the space-based concept is more economical if a retrieval capability is to be provided.

For the polar launches, Figure 10 shows the ground-based nonreusable operational concept to be the most economical. This is because the polar missions require relatively small delta velocities to achieve low altitude orbits, which allows a large proportion of these to be flown with the relatively inexpensive solid propellant stage (FW-4S derivative).

The costs of implementing all logistics operational concepts in all five program activity levels have been developed in the same manner as those presented in Figures 9 and 10 for Program Level C, and they are compared in Figure 12 for Program Levels B through E. (Program Level A does not contain

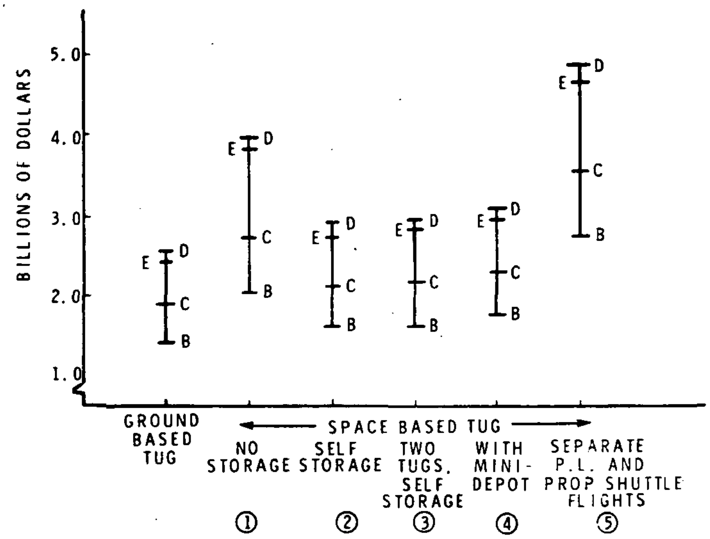


Figure 12. Logistic Program Cost Comparison for 1985-1990 by Program Level and Operational Concept

a reusable tug as an option and has not been included in the comparison.) These costs, which are for tug placement missions only, include both easterly and polar missions for the years 1985 through 1990. The data indicate the same relative pattern of costs at all the program levels; for instance, the lowest cost concept for Program Level B is also the lowest cost concept for Program Levels C, D, and E. Concept 2 is the most economical among the space-based modes at all levels. The concepts with provisions for in-space propellant storage are more economical than the no-storage concepts. The use of the ground-based tug in a ground-based mode is slightly more economical than the heavier space-based tug at all program levels.

SENSITIVITY STUDIES

The sensitivity of the propellant logistic operational concepts to tug mass fraction, shuttle capability, and potential payload growth has been established.

Three different mass fraction tugs (0.877, 0.892, and 0.903), representing data from applicable tug studies, were used to develop the effect of mass fraction on propellant logistic program operation. The results are summarized in Figure 13 using the number of shuttle flights as a direct indication of relative program cost for each case. The tugs are compared as if each could be operated in either a ground-based or a space-based mode in order to show the effect of mass fraction alone.

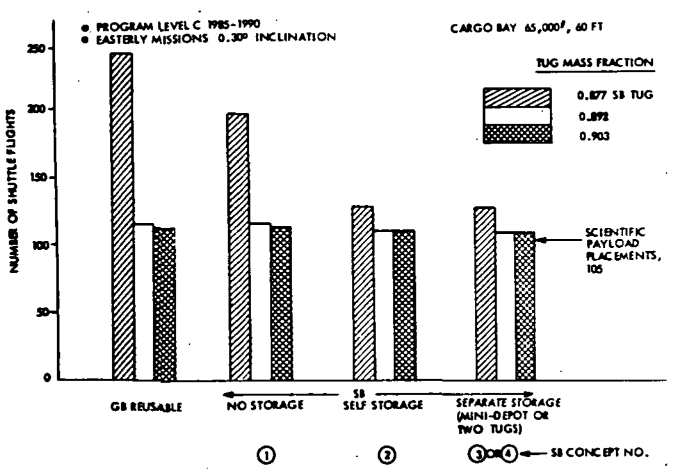


Figure 13. Concept Sensitivities to Tug Mass Fraction

Comparison of the operational concepts indicates a significant advantage for space-based as opposed to ground-based operation

for the low mass fraction tug. For the higher mass fraction tugs, there is little difference among the concepts except for a slight advantage for the space-based concept with storage. In each case there must be at least 105 shuttle flights to carry the 105 scientific payloads in this program. The higher mass fraction tugs are efficient enough so that propellant requirements are not a controlling factor as they are in the case of the low mass fraction tug. For the higher mass fraction tugs, the excess over 105 shuttle flights is determined primarily by payload length or the need to use two tugs in tandem. A conclusion drawn from the data is that for the higher mass fraction tugs, a space-based operation with storage requires slightly fewer shuttle flights and thus is cost competitive with ground-based operation.

Figure 14 shows sensitivities of the selected Concept 2 to variations in

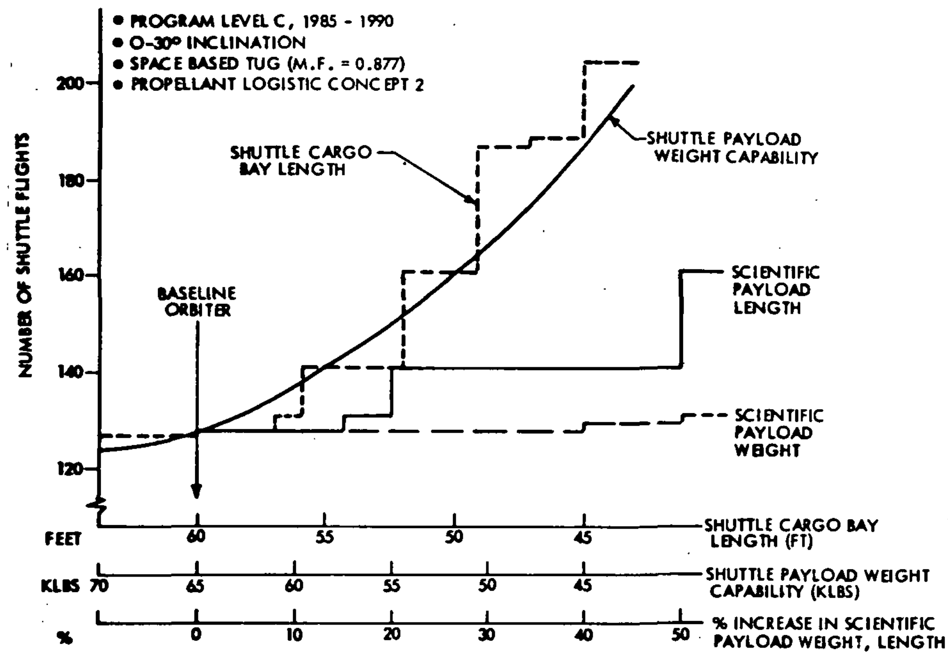


Figure 14. Shuttle Orbiter Flight Sensitivities

the shuttle payload weight and length capability, and to an increase in the weight and length of the scientific payloads in Program Level C, 0- to 30-degree inclinations for the years 1985 to 1990. The data indicate that the logistic operations are very sensitive to shuttle payload capability and to cargo bay length. A decrease from the baseline shuttle to either a cargo bay length of 45 feet or a payload capability of 45,000 pounds would increase the number of shuttle flights required to conduct the program by about 50%. Figure 14 also indicates that the system is less sensitive to growth in payload length and relatively insensitive to growth in payload weight for increases up to 50%.

Table 4 indicates the capability of the three mass fraction tugs to retrieve the payloads contained in the placement missions for Program Level C for the years 1985 to 1990. The number of shuttle flights required to

Table 4. Propellant Logistics Concept Sensitivity to Tug Mass Fraction for Retrieval Missions

		Number of supporting shuttle flights required by operational concepts			
			Space Based		
Tug Mass Fraction	Number of Payloads Retrieved out of 105 in Program	Ground Based	Concept 1 No Storage	Concept 2 Self Storage	Concepts 3 or 4 2 tugs or Mini-Depot
0.877 (SB tug)	66	125	119	76	76
0.892	93	108	93	93	93
0.903	93	93	93	93	93

support these retrieval missions are listed in the table for several logistics concepts. The data demonstrate that space-based operation is more cost-effective for a retrieval capability than ground-based operation for all except the highest mass fraction tug.

PROPELLANT TRANSFER ANALYSIS

The propellant transfer analysis for this study consisted of a comprehensive investigation to define the transfer techniques, interface requirements, functional characteristics, and general configurational requirements for the various propellant logistics concepts which were developed. The principal situation analyzed was the delivery of propellants from the ground to space-based vehicles using the space shuttle as the delivery vehicle.

Cryogenic propellant can be transferred from one space vehicle to another by either of the following two methods: (1) fluid flow which requires the transfer of propellant between elements by some fluid flow techniques, and (2) modular transfer, which involves the transfer of packaged or contained propellant from one vehicle to another.

During the initial phase of the propellant transfer analysis, it was established that the configuration, operational characteristics, and require-

ments of the space program vehicles were such as to preclude the modular transfer of propellant as a primary mode.

A number of candidate techniques for fluid flow in-space transfer of cryogenic propellants has been defined in studies conducted by NASA, North American Rockwell, and other contractors and agencies. These studies conclude that it is necessary to maintain rigorous control of certain propellant and environmental conditions to achieve effective propellant transfer. These control functions are interrelated and can be categorized in different ways. For the purpose of this study, the required control functions have been defined as (1) liquid/vapor interface control; (2) receiver tank thermodynamic control; (3) liquid expulsion, and (4) net positive suction pressure (NPSP) control. Figure 15 shows sketches of candidate techniques for these four control functions.

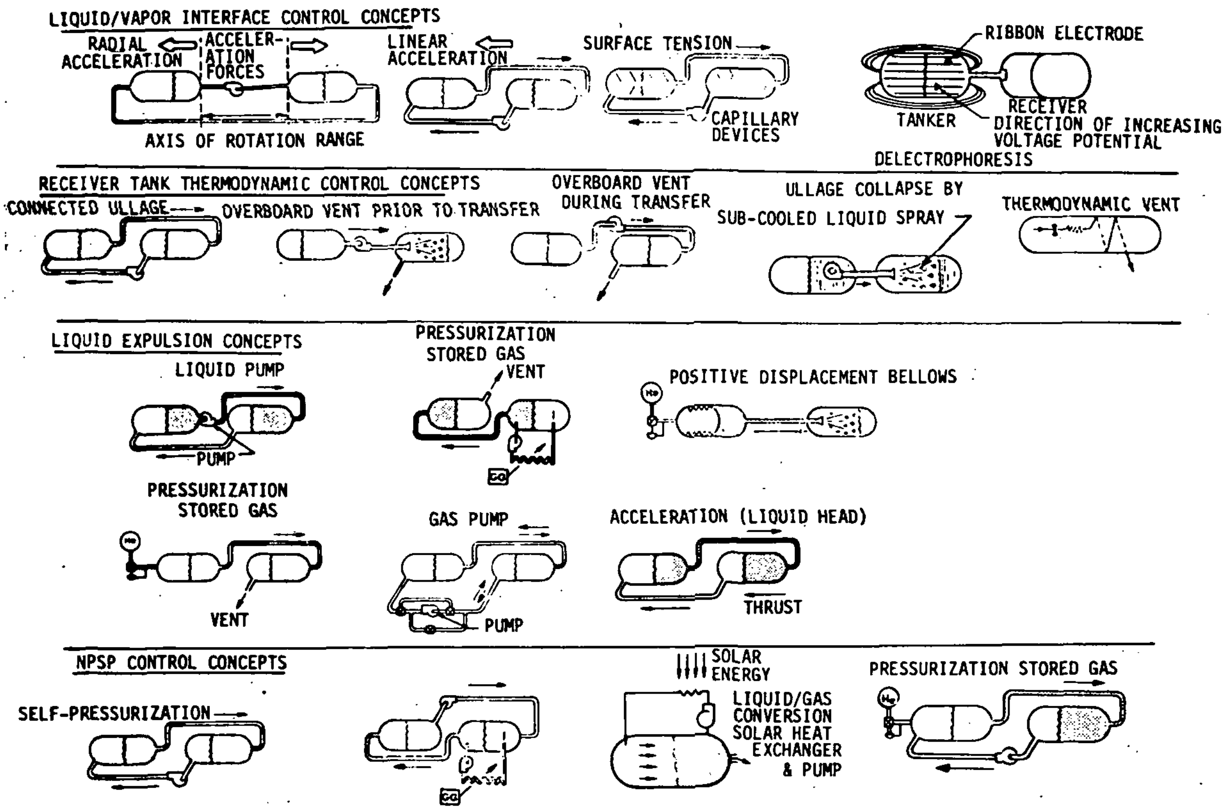


Figure 15. Propellant Transfer Techniques

Comprehensive trade studies were conducted to support the selection of the most favorable propellant transfer concept. The criteria used for selection included propellant transfer losses, compatibility with user and logistic vehicle systems, and development risk. The baseline concept selected provides for control of the critical transfer functions in the following manner: Rigid docking of the propellant module to the user

vehicle is required and the assembly separated from the shuttle orbiter during transfer; linear acceleration of the vehicle/module assembly provides liquid/vapor interface control; the ullage of the vehicle tanks and propellant module tanks are connected to provide receiver tank thermodynamic control; a gas pump in the ullage return line provides liquid expulsion by raising the pressure of the propellant module tanks above that in the user vehicle tanks; and an active pressurization system provides for NPSP control.

Electrical power, communications equipment, and computational systems for control of the transfer operation and for attitude control are provided by the existing user vehicle systems. A low-thrust acceleration system along with most of the system components required to perform the fluid transfer operation are located in the propellant logistic module. Location of this equipment in the module permits ground maintenance since the module is returned to earth after each logistic support mission. It also precludes the addition of its weight to the user vehicles, which would penalize their operational capability.

As a result of the analysis conducted, the following general conclusions were formulated:

1. In-space liquid flow cryogenic propellant transfer is feasible for logistic support of all the space program elements considered for the ISPLS study.

2. The order of preference and qualifying constraints for orbital propellant transfer are as follows:

   a. Modular - when receiver configuration and operational constraints permit.

   b. Radial Acceleration - when overall center of gravity (c.g.) and operational constraints permit.

   c. Linear Acceleration - requires a longer life propulsion system and moderately higher propellant losses.

3. Fluid transfer losses in the range of 0.6 to 5.7% are predicted for fluid flow propellant transfer using acceleration (radial or linear) for liquid/vapor interface control.

4. The fluid flow transfer system configuration is predominantly dependent upon the configuration of the interfacing user vehicle.

Since the technique utilized for liquid/vapor interface control tends to be the driving function in the overall selection of the subsystems and operational procedure for the complete transfer system, the analysis conducted included an evaluation of the propellant losses involved in both radial and linear acceleration propellant settling. A comparison of linear versus rotational propellant transfer losses associated with both source

tank residuals and thruster propellant for acceleration is shown in Figures 16 and 17. Figure 16 presents losses as a function of transfer time for linear acceleration levels of 10^{-3} g, 10^{-4} g, and 10^{-5} g. The minimum linear propellant transfer loss for a reasonable transfer time occurs at a 10^{-4} g acceleration level and a 10-hour transfer time. Figure 17 presents losses as a function of acceleration for a 10-hour rotational transfer time. At the optimum radial acceleration level of 8×10^{-4} g, propellant losses are much less than for linear transfer (0.35% of the amount transferred by rotation as compared to 1.9% for linear transfer). Also shown in the figure are the losses for a five-hour and a 20-hour rotational transfer time.

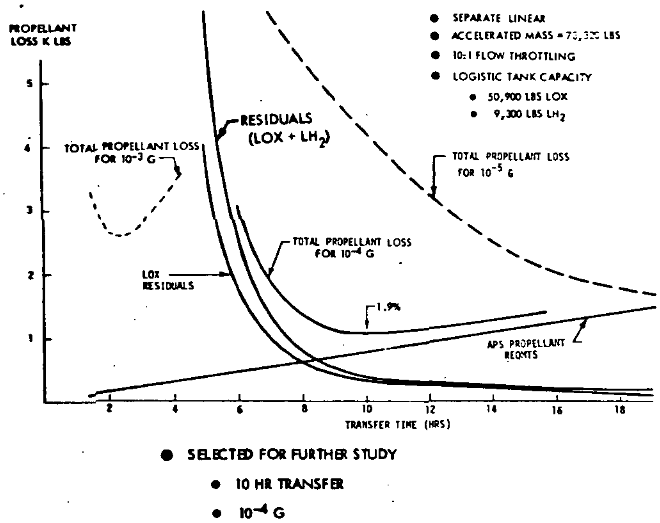


Figure 16. Linear Acceleration Propellant Losses, Direct Transfer to Space-Based Tug

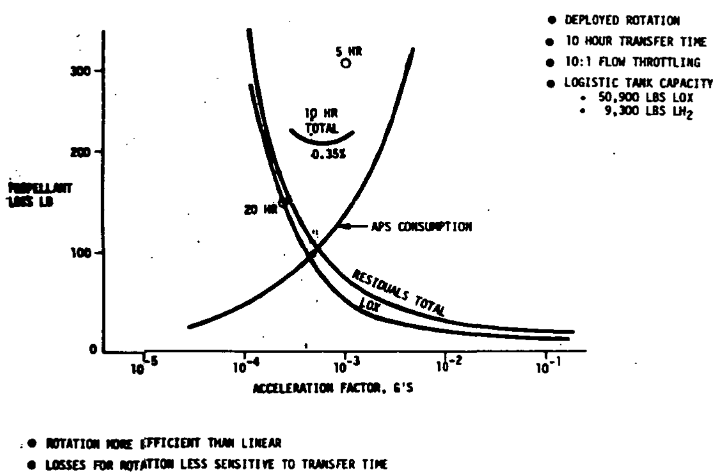


Figure 17. Rotational Transfer Propellant Losses, Direct Transfer to Space-Based Tug

Another potential problem associated with the long-duration transfer operation is the effect of low-thrust acceleration on the spacecraft trajectory. As a result of an analysis of this problem, it was learned that continuous cross-plane thrusting perpendicular to the initial orbital plane will ideally produce an orbital path that will return the vehicle to its initial orbit once each revolution. Under these ideal conditions, no distance, inclination, or velocity differentials exist at this point of coincidence. When earth oblateness effects were introduced into the computerized analysis, it was determined that a small increasing distance differential occurred after each orbit. This differential is approximately one quarter of a nautical mile after the first orbit, and approximately seven nautical miles when extrapolated to 10 orbits or 15 hours.

The results are presented in Figure 18, along with a comparison with an alternate concept evaluated utilizing in-plane thrusting. The in-plane concept was found to be unstable, resulting in earth impact after several orbits and thus was not considered any further.

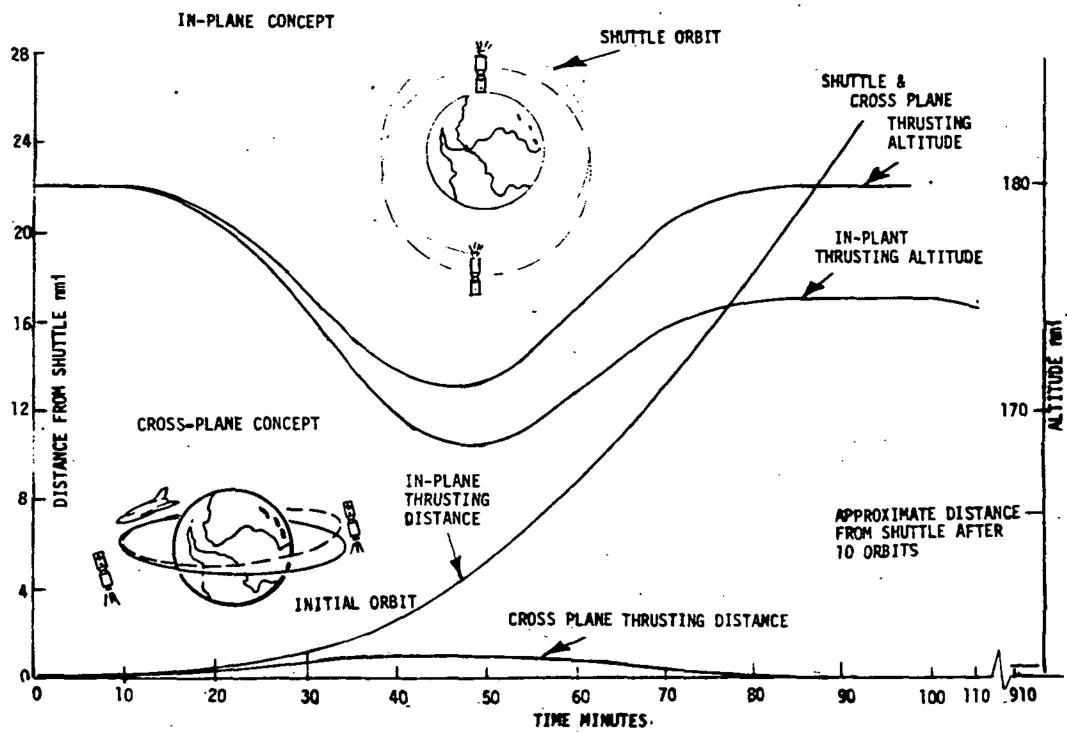


Figure 18. Linear Acceleration/Propellant Settling, Orbital Mechanics

Analyses and trade studies were conducted to establish the relative characteristics of the concepts considered and to select a baseline configuration for each of the subsystems of the complete propellant transfer system. The results of these analyses are presented in Section 6 of Volume II and Section 6 of Volume III.

SELECTED CONCEPT DESCRIPTION

As developed in previous sections, the selected propellant logistic concept requires direct delivery of propellant by the shuttle to the space-based tug, and the CIS or the RNS. These vehicles will accumulate and store the propellants required for their space-based station-keeping and operational missions in their own tanks. Separate depots are not required. The selected concept for the tug mission operation is illustrated in Figure 11.

The logistic module used to carry the propellant in the shuttle is the only major new hardware element of the selected concept. Its interfaces with the shuttle as well as the tug, CIS, or RNS will require minor modifications to these vehicles to accommodate its use. The basic module configurations and requirements for refueling the tug, the CIS, and the RNS are the same except for tank sizes; the RNS module carries only hydrogen and occupies the full shuttle cargo bay length; the tug and CIS modules carry approximately the same amounts of oxygen and hydrogen.

Logistic Module

The operational requirements for the logistic module involve relatively short-duration missions to and from space. Propellant storage in the module is required for a maximum interval of about seven days; however, the modules must be designed for repeated missions and hence long life. The tug supportive propellant logistic module shown in Figure 19 illustrates the

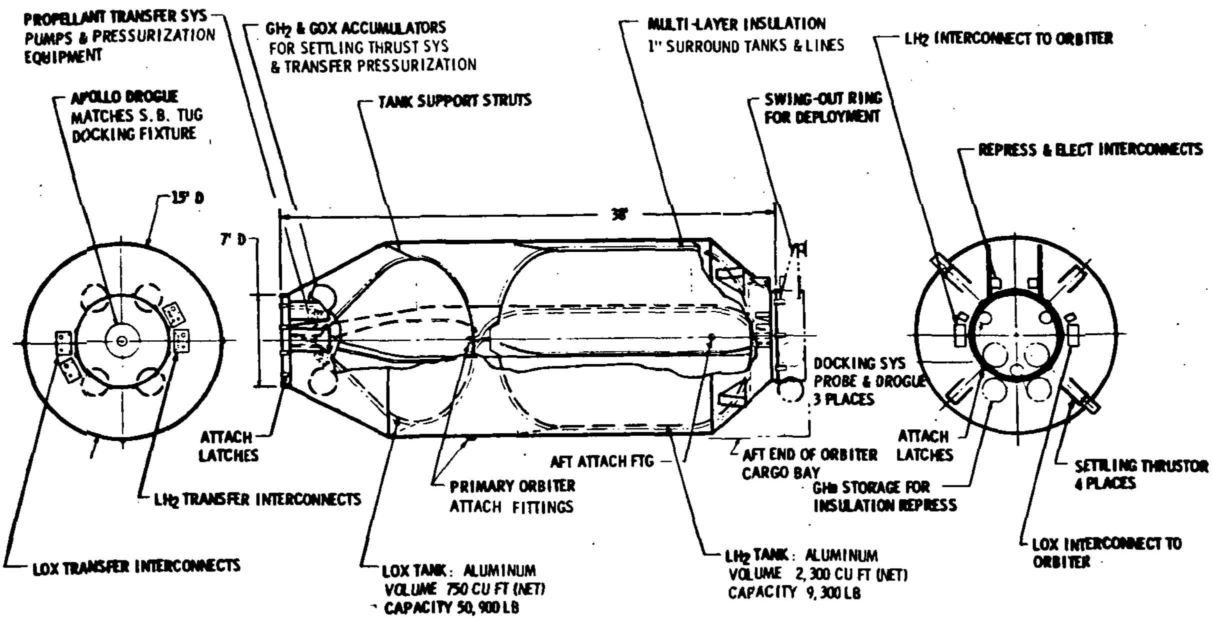


Figure 19. Tug Supportive Propellant Logistic Module

design concept for all three tanks. It is approximately 40 feet long and weighs about 5000 pounds including the swing out-ring used to aid deployment of the tank from the shuttle. A conical-shaped oxygen tank is used to facilitate propellant transfer and reduce residuals in the low-g transfer environment. The basic structure consists of the LO_2 and LH_2 tanks supported within an outer shell, with a user docking fixture at one end and provisions to dock with the deployment ring that is part of the cargo installation in the orbiter on the other. The shell is of composite

material. The tanks are aluminum and are supported by S-glass filament-wound struts. The tanks and lines are insulated with a one-inch thickness of multilayer single aluminized Kapton insulation. The insulation must be purged with inert gas during ground operations and during the return flight from orbit to preclude degradation of its insulating properties.

Line interconnect mechanisms on the module extend and engage the transfer lines with the user vehicle. The active mechanism is on the logistic module, which imposes a minimum weight penalty on the user vehicles. The inter-connects have a floating alignment capability and engage electrical and fluid lines separately. Propellant transfer components installed on the module include lines, valves, sensors, and controls involved with ground filling, system checkout, orbital storage, and orbital propellant transfer. Gas generators, heat exchanger, turbopumps, and gaseous accumulators are utilized to pressurize the source and receiver tanks prior to and during the transfer operation to avoid two-phase flow. This system and its components are also used to condition propellant for supply to the liquid settling thrusters. The low energy thrusters provide linear acceleration for propellant liquid/vapor interface control during transfer. The thrusters are located at the opposite end of the module from the user and exhaust along the module, toward the user, to provide proper propellant settling direction.

The thruster housings are deployable, extending beyond the module shell in operation (to minimize impingement), and retract to fit within the orbiter cargo bay.

Interfaces

The logistic module will be under the physical and functional control of either the shuttle or the user vehicles at all times. It will obtain electrical power and data management support for control of the propellant transfer operation from the user vehicles. About 400 watts of power are required.

The functional interfaces of the logistic module are illustrated in Figure 20. The orbital transfer line interfaces are at a minimum with a supply and ullage return line for each propellant and three electrical connections. The line interface to the shuttle appears more complex but the nine fluid lines shown are necessary for the indicated functions (most lines share functions) and are comparable to the interfaces required by many other orbiter cargos. The structural attachments are based on the support system proposed by the NR shuttle design study. With separate logistic modules for each user, the module docking fixtures will be matched to the docking system chosen by the user vehicle. Propellant logistic considerations do not impose commonality of docking fixture on the user vehicles. In summary, the interfaces do not impose stringent or major change on either the shuttle or the user vehicles but do require provisions for the indicated power, control, and fluid interconnections.

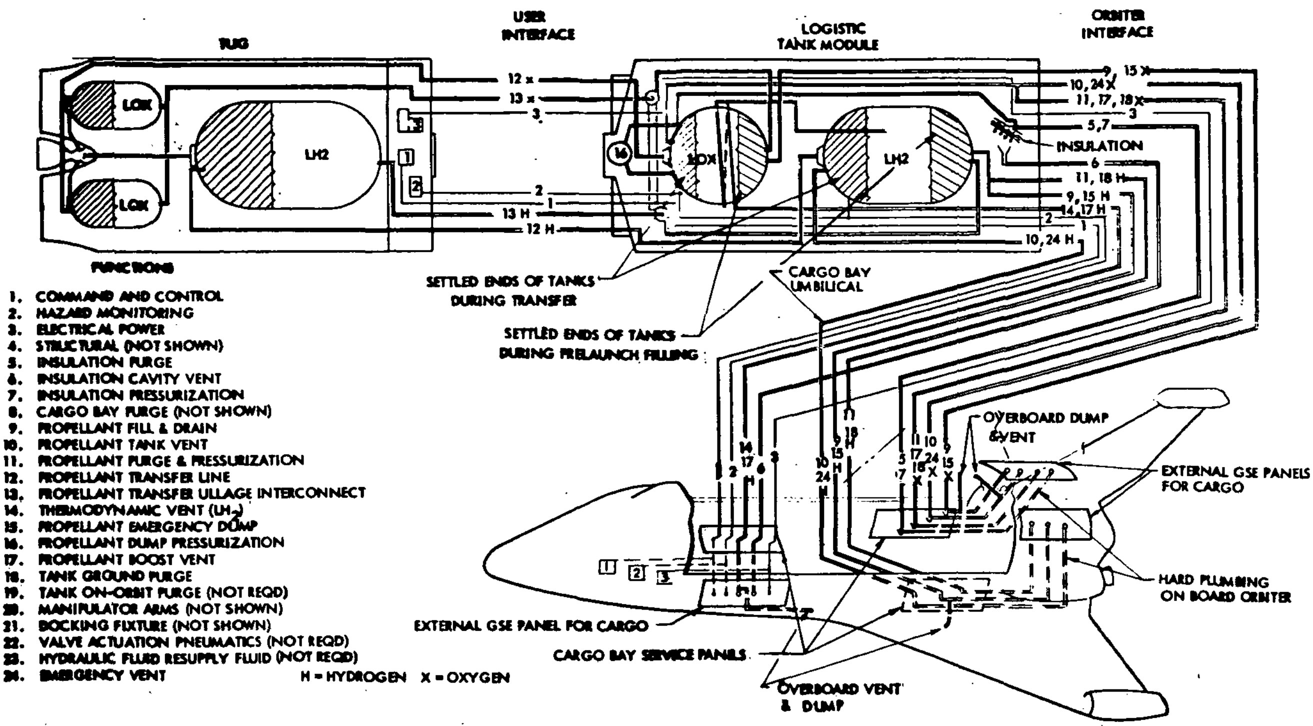


Figure 20. Logistic Module Line Interface Schematics

<u>Systems Integration</u>

Finally, a number of technology areas have been defined which involve an interaction of the elements of the overall transfer system. These areas, categorized as systems technology, include the following: (1) interface requiremets and definition for the logistic module/space shuttle combination; and (2) interface requirements and definition for docking and line mating fixtures.

LOGISTICS IMPLEMENTATION PLAN

The major steps for confidently achieving the development and demonstration of orbital propellant transfer and storage with an initial operational capability (IOC) early in 1985 are identified, integrated, and time-phased in a program implementation plan presented on Figure 21. The plan provides for a disciplined development leading from the early supporting research and technology studies into the Phase D operations.

The impact that the in-space propellant logistics program will have on the various government facilities and equipment for the conduct of manufacturing, testing, and launch operations has been identified. Launch site facility modifications include the addition of independent propellant flow control complexes, the addition of propellant transfer lines, an increase in LH_2 storage tank pressure from 60 to 65/75 psig, and additional controls in the launch control center for propellant loading and servicing operations.

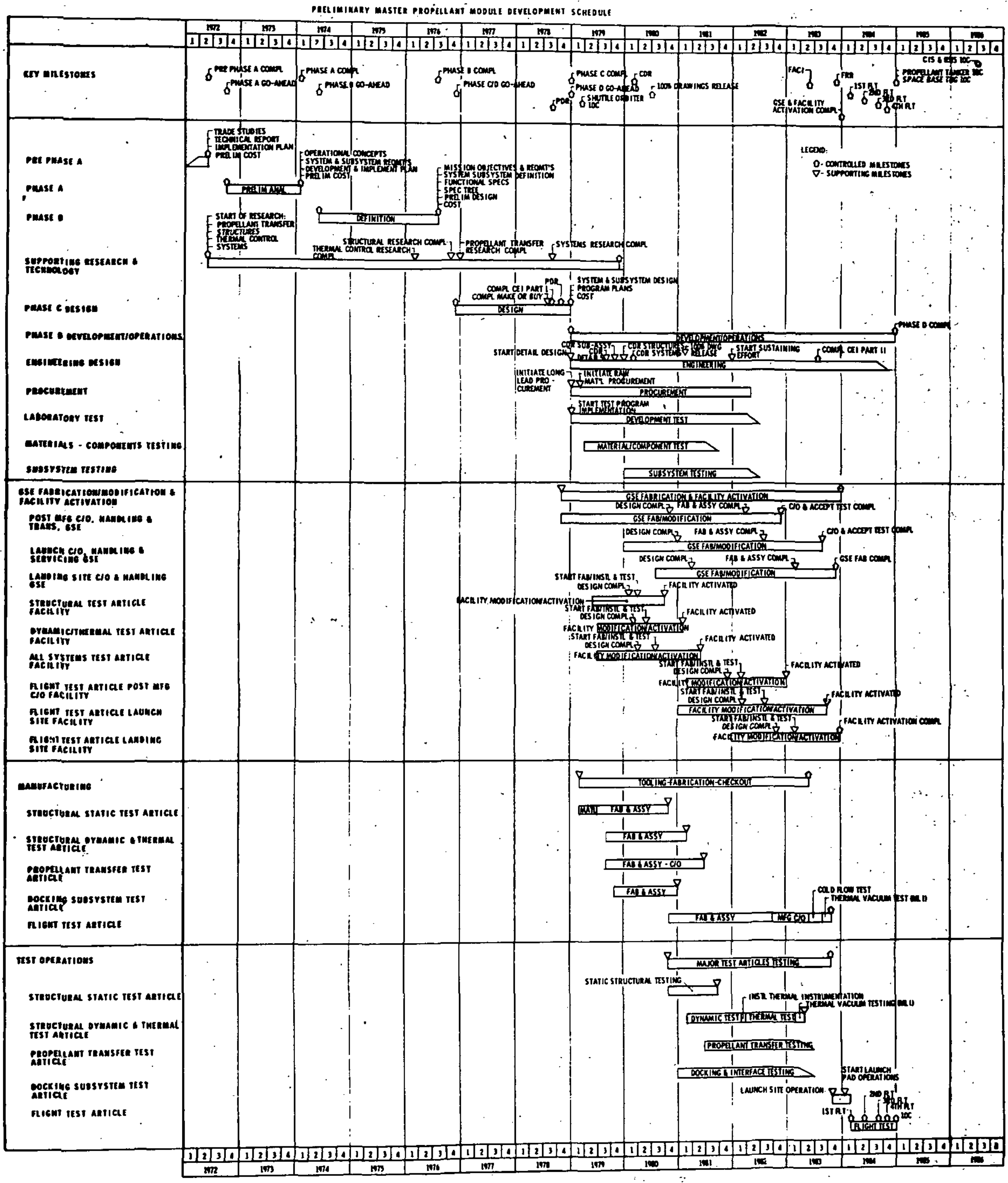


Figure 21. Implementation Schedule

The number of launch pads required to support each of the space traffic models has been derived. Program Level C, which corresponds to the Fleming Model activity level, can be accommodated with existing launch facilities.

Local manufacture of LO_2 in support of traffic models "D" and "E" for CIS and RNS is of concern from production and utilization standpoints. However, existing production capability is sufficient for all other program levels. Propellant utilization impact is minimal compared to the shuttle propellant requirements.

Table 5. Propellant Logistics Module Program Costs

Cost Elements	Program Level C
SR&T	$ 13.3M
DDT&E	88.8
Flight Test	52.4
Facilities	3.2
Total Fixed Cost	$157.7M
PM Production	18.3
PM Operations	25.7
Total Estimated Cost	$201.7M

Program costs for the propellant modules necessary to implement an orbital propellant transfer capability are presented in Table 5. These costs include supporting research and technology tasks, DDT&E, production, and operations costs. Flight test costs, which include the use of the shuttle in four flights, are shown separately from other DDT&E costs. The production and operations costs are those which would be required for the use of the module in the NASA mission Program Level C.

The costs do not include the delivery of propellants to orbit by the shuttle, tug operations, NASA management, nor tracking and data acquisition.

SUPPORTING RESEARCH AND TECHNOLOGY

This study has revealed specific technical problem areas associated with the storage and transfer of propellants in space. These problems will require supporting research and technology in order to provide an efficient and reliable in-space propellant logistics capability. These problems have been categorized into the following areas: propellant transfer, structures, high-performance multilayer insulation, cryogenic thermodynamic control, and systems integration.

Propellant Transfer

A suitable LO_2/LH_2 propulsion system must be developed with long-duration burn capability at thrust levels of 8 to 20 lb. Better and expanded data on source tank liquid residuals resulting from ullage pull-through are required. Additional experiments and analyses will also be required to evaluate vehicle/propellant dynamic interaction, quantity gauging under low-g conditions, and capillary systems for zero-g propellant transfer. This last area represents a possible transfer alternative which could be used in conjunction with the baselined linear acceleration mode.

Structures

Technology problems in the structures area are characteristic of those encountered with thin-wall, lightweight cryogenic tankage. A program to

determine the material properties controlling fracture mechanics is recommended. For further improvements in tank strength to weight ratio, advanced composite materials should be evaluated.

Insulation

Ability to perform the orbital transfer presupposes that high-performance multilayer insulation (MLI) has been developed and can be successfully attached to the logistic module. To assure this capability, applied research on MLI composed of aluminized polyimide (duPont trade name: Kapton) film material is required.

Cryogenic Thermodynamic Control

Heat leakage to the logistic module during boost and orbital flight will cause temperature and pressure rise in the contained cryogens. Under boost conditions temperature stratification and pressure rise can be predicted reasonably well. However, this is not the case under low-g conditions. Hence, supporting studies to develop the capability to predict stratification and pressure rise under low-g conditions are proposed. This heating may result in excessive propellant temperatures and pressures; therefore, studies to define a thermodynamic vent system for temperature and pressure control of the logistic module propellants should be carried out.